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TREATMENT OF MATERIALS

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OPTIMIZATION OF DIAMOND DRILLING USING AN EXTREME EXPERIMENTAL DESIGN

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The results of experimental studies in selecting optimum characteristics for diamond drills and optimum treatment procedures for drilling holes 1 – 70 mm in diameter in hard brittle nonmetallic materials such as quartz, ceramics, glass, and glass ceramics are considered. To obtain experimental-mathematical models, a randomized experimental design was used at the screening stage, i.e., a half-replica of the full factorial experiment 2^3, and an orthogonal compositional design of the second order of type 3^5 was used at the main stage. The diamond drilling process was optimized using simplex methods. The correlation of the estimated values with experimental data showed the adequacy of the results obtained.

The use of solid and brittle nonmetallic materials (quartz, glass ceramics, glass, and ceramics) calls for upgrade of mechanical treatment methods. For this purpose tools with high abrasive characteristics based on natural or synthesized diamonds are developed and actively applied in the manufacturing industry. The efficiency and quality of diamond treatment of solid and brittle nonmetallic materials can be improved by optimization of treatment regimes. An important instrument for solving this problem is a mathematical experimental design using general principles of probability theory and mathematical statistics.

It is advisable to apply probabilistic-statistical methods to study complex technological processes and experimental data processing to determine the reliability, accuracy, and sufficiency of data for making certain decisions and also to develop mathematical-statistical models to be used for the process optimization.

The process considered is a complex system, and we will attempt to account for the mutual influence of factors to obtain an integrated representation of treatment in a mathematical form.

The factors that have an effect on the output parameters of the model were identified based on empirical data and results of analytical modeling [1].

The model parameters are the following:

– axial cutting force P_f;
– roughness of the surface treated R_a;
– average width of chips at the hole inlet ξ;
– specific consumption of diamonds q;
– resistance of the drill l.

The factors influence the model parameters are as follows:

x_1) cutting velocity v;
x_2) feed S;
x_3) size of diamond grains G;
x_4) concentration of diamonds C;
x_5) sort of diamond;
x_6) type of binder material;
x_7) material of the part treated;
x_8) type of lubricant-coolant (LC) T_{LC};
x_9) lubricant-coolant pressure P_{LC};
x_{10}) lubricant-coolant flow rate Q_{LC}.

The total number of factors is too high for varying, and consequently studies were carried out to simplify the model and reduce the number of its factors.

A first series of experiment was carried out using a randomized experimental design for a preliminary investigation of the response surface on a chosen site. To obtain an experiment design, the factors investigated were split into two groups, and a semireplica of a full factorial experiment of type 2^5 was used for each group. The initial data are listed in Table 1 and the results are listed in Table 2.

Based on the data from Table 2, scattering diagrams were constructed for each of 10 factors, and factors significant for the diamond drilling process were identified using the η-rule [2]. An example of a scattering diagram is shown in Fig. 1. The significant factors of the process are unequally distributed among the controlling variables. As a consequence of ranking, the following data were obtained.

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TABLE 1

No.	x_1, m/sec	õ$_2$, mm/min	x_3, µm	x_4, %	x_5	x_6	x_7	x_8	x_9, MPa	x_{10}, liter/min
1	3	10	400/315	150	AS50	M1	22KhS	ÉMUS	0.3	8
2	1	30	400/315	50	AS160	M1	K8	ÉMUS	0.1	8
3	1	30	400/315	150	AS50	M1	K8	ÉMUS	0.3	2
4	1	10	400/315	150	AS160	M1	K8	NGL-205	0.3	8
5	3	30	400/315	150	AS160	M1	22KhS	NGL-205	0.3	2
6	1	10	200/160	150	AS50	OPM	22KhS	ÉMUS	0.3	2
7	1	30	200/160	50	AS50	OPM	K8	NGL-205	0.3	2
8	3	30	200/160	150	AS50	OPM	22KhS	NGL-205	0.3	8
9	1	10	200/160	50	AS160	M1	22KhS	ÉMUS	0.1	2
10	1	10	400/315	50	AS50	OPM	22KhS	ÉMUS	0.1	8
11	3	10	200/160	50	AS50	OPM	22KhS	NGL-205	0.1	2
12	3	30	400/315	50	AS50	OPM	K8	ÉMUS	0.3	8
13	3	10	400/315	50	AS160	M1	K8	NGL-205	0.1	2
14	3	10	200/160	150	AS160	OPM	K8	NGL-205	0.1	8
15	1	30	200/160	150	AS160	M1	22KhS	NGL-205	0.1	8
16	3	30	200/160	50	AS160	OPM	K8	ÉMUS	0.1	2

TABLE 2

No.	P_f, N	R_a, µm	ξ, mm	q, mg/cm	l, mm
1	163	0.9	0.12	0.20	25
2	144	2.4	0.21	0.15	500
3	126	2.1	0.20	0.14	450
4	60	1.5	0.18	0.13	700
5	275	0.9	0.11	0.18	15
6	213	0.6	0.08	0.22	30
7	162	1.9	0.17	0.13	350
8	312	0.8	0.11	0.25	5
9	187	0.6	0.07	0.19	15
10	212	1.4	0.09	0.21	10
11	200	0.8	0.07	0.19	15
12	138	2.4	0.20	0.15	550
13	84	2.3	0.24	0.16	600
14	108	1.5	0.15	0.14	570
15	300	0.7	0.12	0.20	10
16	168	1.7	0.19	0.12	440

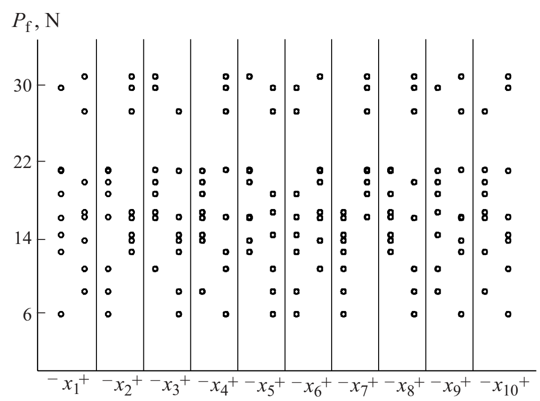

Fig. 1. Scattering diagram of P_f.

Significant Factors of the Process

Model parameters	Factors influencing the parameter
Axial cutting force	Feed, diamond grain size, diamond concentration, sort of diamond, material of part treated
Roughness of surface treated	Cutting velocity, feed, diamond grain size, diamond concentration, material of part treated
Average width of chips at the hole inlet	Feed, diamond grain size, diamond concentration, material of part treated, LC flow rate
Specific consumption of diamond	Cutting velocity, feed, sort of diamond, type of binder, material of part treated
Drill resistance	Cutting velocity, feed, sort of diamond, material of part treated, LC flow rate

Based on analytical modeling [1], the following quantitative parameters were chosen to characterize, respectively, the material of a product treated, the binder type, and the sort of diamond: the microhardness of product material H; the bending strength of binder σ_b^{bin}, and the compression strength of diamond powder σ_c^{dia}.

Thus, it is necessary to determine the following dependences to implement optimization:

$$P_f = f(S, G, \sigma_c^{dia}, H);$$

$$R_a = f(\nu, S, G, C, H);$$

$$\xi = f(S, G, C, H, Q_{LC});$$

$$q = f(\nu, S, \sigma_c^{dia}, \sigma_b^{bin}, H);$$

$$l = f(\nu, S, \sigma_c^{dia}, H, Q_{LC}).$$

TABLE 3

Factor	Variation interval	Level		
		main	upper	lower
x_1, m/sec	1	2	3	1
x_2, mm/min	10	20	30	10
x_3, μm	100	180 (200/160)	280 (315/250)	80 (100/80)
x_4, %	50	100	150	50
x_5	30	56 (AS60)	86 (AS100)	26 (AS20)
x_6	75	130 (OPM)	205 (M)	55 (M1)
x_7	500	1000 (STM-1)	1500 (TsM332)	500 (sheet glass)
x_9, MPa	0.1	0.2	0.3	0.1
x_{10}, liter/min	3	5	8	2

It is known a priori that the dependences considered can be described by a polynomial of the second order:

$$Y = B_0 + B_1 x_1 + B_2 x_2 + B_3 x_3 + B_4 x_4 + B_5 x_5 + B_{12} x_1 x_2 + B_{13} x_1 x_3 + B_{14} x_1 x_4 + B_{15} x_1 x_5 + B_{23} x_2 x_3 + B_{24} x_2 x_4 + B_{25} x_2 x_5 + B_{34} x_3 x_4 + B_{35} x_3 x_5 + B_{45} x_4 x_5 + B_{11} x_1^2 + B_{22} x_2^2 + B_{33} x_3^2 + B_{44} x_1^4 + B_{55} x_1^5,$$

where B_{ij} are the model coefficients; x_i are the process factors.

An orthogonal compositional second-order design of type 3^5 was accepted as the experimental design. The factor variation intervals were determined as a consequence of preliminary experiments and analytical modeling (Table 3).

In view of the orthogonality of the design, all regression coefficients are calculated independently of each other using the following formulas:

$$b_0 = \frac{1}{n_0} \sum_{u=1}^{n_0} Y_{0u};$$

$$b_i = \frac{\sum_{j=1}^{N} x_{ij} Y_j}{\sum_{j=1}^{N} x_{ij}^2};$$

$$b_{ij} = \frac{\sum_{j=1}^{N} x_{ij} x_{ij} Y_j}{\sum_{j=1}^{N} x_{ij}^2},$$

where n_0 is the number of experiments at the center point of the design; u is the consecutive number of the replicate experiment; Y_{0u} and Y_j are the values of the parameter considered in the uth and the jth experiments; j is the consecutive number of the experiment; i is the consecutive number of the factor; x_{ij} is the ith factor in the jth experiment.

Based on the modeling results, regression equations were obtained for the parameters considered. After verifying the adequacy of the model obtained using the F-criterion (Fisher criterion), mathematical models of the processes investigated were constructed. For instance, such a model for P_f has the following form:

$$P_f = 22.6710 - 9.271 \times 10^{-3} S + 9.69 \times 10^{-4} S^2 - 3.1826 \times 10^{-2} G + 1.62 \times 10^{-5} G^2 - 2.8056 \times 10^{-2} C + 1.77 \times 10^{-4} C^2 - 0.42256 \sigma_c^{dia} + 2.97 \times 10^{-3} \sigma_c^{dia\,2} - 3.992 \times 10^{-3} H + 7.856 \times 10^{-6} H^2 + 6.8 \times 10^{-5} SG + 5.98 \times 10^{-5} SC + 2.73 \times 10^{-5} S\sigma_c^{dia} + 5.485 \times 10^{-4} SH - 2.01 \times 10^{-5} GS + 2.45 \times 10^{-5} G\sigma_c^{dia} + 9.24 \times 10^{-7} GH + 2.35 \times 10^{-5} C\sigma_c^{dia} + 3.28 \times 10^{-7} CH - 2.35 \times 10^{-6} H\sigma_c^{dia}.$$

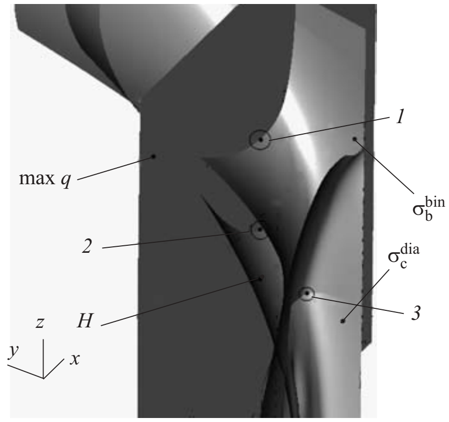

Fig. 2. Results of modeling the mutual effect of parameters that influence specific consumption of diamond q depending on the cutting velocity v.

Mathematical models for other parameters were calculated similarly.

The second stage of optimization of the diamond drilling process is identifying the coordinates of the local optima of the models constructed using the simplex method. The efficiency of drilling was taken as the criterion of optimality. The principal constructions were implemented in the $v - S$ coordinate system, and the dependence obtained were used to find the limiting surfaces. Plots (surfaces) describing the mutual effect of the parameters were constructed for the dependences obtained. An example of a set of surfaces for specific consumption of diamonds is shown in Fig. 2, which represents the limitation surface for a maximum specific consumption and the surfaces for the calculation of optimum efficiency parameters [*1*) based on $v - \sigma_c^{dia}$; *2*) based on $v - H$; *3*) based on $v - \sigma_b^{bin}$].

The analytical and experimental mathematical models were used to develop algorithms and specialized software to calculate tool parameters and treatment conditions taking into account the following limitations: $R_a \leq 1.6$ μm, $\xi \leq 0.10$ mm, $q \leq 0.30$ mg/mm, $l \geq 200$ mm.

TABLE 4

Parameter*	Horseshoe-shaped drill of diameter 1 – 5 mm drilling		Circular drills of diameter 6 – 70 mm drilling	
	glass ceramics	quartz	glass	ceramics
Cutting velocity, m/sec	5	5	3	3
Feed, mm/min	5	5	29	8
Size of diamond grains, μm	100/80	125/100	160/125	200/160
Concentration of diamonds, %	350	350	250	250
Sort of diamond	AS50	AS65	AS50	AS80
Lubricant-coolant flow rate, liter/min	8	8	6	6

* Binder M was used in all cases.

Computerized calculations using the models described produced optimum values for the tool parameters and treatment conditions (Table 4).

The axial cutting force calculated for the specified drill parameters and treatment regimes is equal to 53 and 67 N for drilling holes 3 mm in diameter in glass ceramics and quartz, respectively, and 141 and 253 N for drilling holes 26 mm in diameter in glass and ceramics, respectively.

A comparison of the calculated values with experimental data shows the adequacy of the results obtained. Thus, the axial cutting force (which is the main parameter used in adaptive control systems for diamond drilling) in verification experiments amounts to 50 and 70 N in drilling 3-mm hole in glass ceramic STM-1 and in quartz, respectively, and 130 and 250 N, respectively, in drilling 26-mm hole in sheet glass and in ceramic TsM-332. The mean error in the above experiments was 5.5%.

The use of the modeling results in the form of specialized software for the calculation of efficient cutting regimes for various combinations of tools and materials makes it possible to improve the process efficiency, to reduce the number of tool dressings, and to decreases the probability of emergency failures.

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